On Integrating Cloud-Radar-Derived Arctic Ice Cloud Properties into the Radiative Transfer Model "Streamer"

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1. Introduction

Millimeter-wavelength cloud radars can potentially provide a vast dataset on ice cloud optical properties. The problem arises, however, of how best to integrate the radar-retrieved ice microphysics into radiative transfer (RT) simulations. Aside from the radiative effect of the random retrieval errors, two incompatibilities arise:
1) cloud radar does not sense potentially radiatively-important small particles
2) the vertically-pointing cloud radar is only weakly responsive to particle habit details that may be consequential for short- and longwave radiation.

Here we evaluate the impact of these two effects upon the net cloud radiative heating rate using one well-documented case study with available insitu aircraft data on the particle size distributions. On April 28, 1998, an optically-thin single-layer ice cloud advected over the cloud radar at the Surface Heat and Energy Budget of the Arctic experiment (Uttal et al., 2002). The cloud optical depth could be independently determined from an Atmospheric Emitted Radiance Interferometer (Revercomb et al., 1993). A radar estimate of the volume extinction coefficient and particle size is performed (Matrosov et al. 2002), and the radiative transfer code Streamer is utilized for the short- and longwave RT simulations.

2. Radar Retrieval of the Volume Extinction Coefficient

Fig. 1 shows the a) radar reflectivity and b) Doppler velocity for this case. A radar-only vertically-resolved retrieval of the particle median size Do and volume extinction coefficient β has been recently developed (Matrosov et al., 2002). Advantages include: 1) reliance on radar alone extends the retrieval's range of applicability, 2) a direct retrieval of β is more easily compared or tuned against another independent measure of the cloud optical depth τ, and, 3) once β and Do are retrieved and β perhaps tuned, Do can be varied without impacting the value of β. First, Do is inferred using a Doppler velocity-particle size relationship. Then, β is estimated from the radar reflectivity and Do. For this particular case, the β estimate could be tuned using the AERI-determined τ. This tuned estimate of β is shown in Fig. 2a. The cloud optical depth corresponding to the original radar-only estimate of β is shown in Fig. 2c. Over the ten hours of this case, the radar-only τ is either in agreement with or an overestimate relative to the AERI τ. Over the entire SHEBA year, radar-only estimated optical depths were about 25% lower than AERI optical depths (S. Matrosov, pers. comm.), consistent with the expectation that the cloud radar can miss small yet radiatively-important particles.
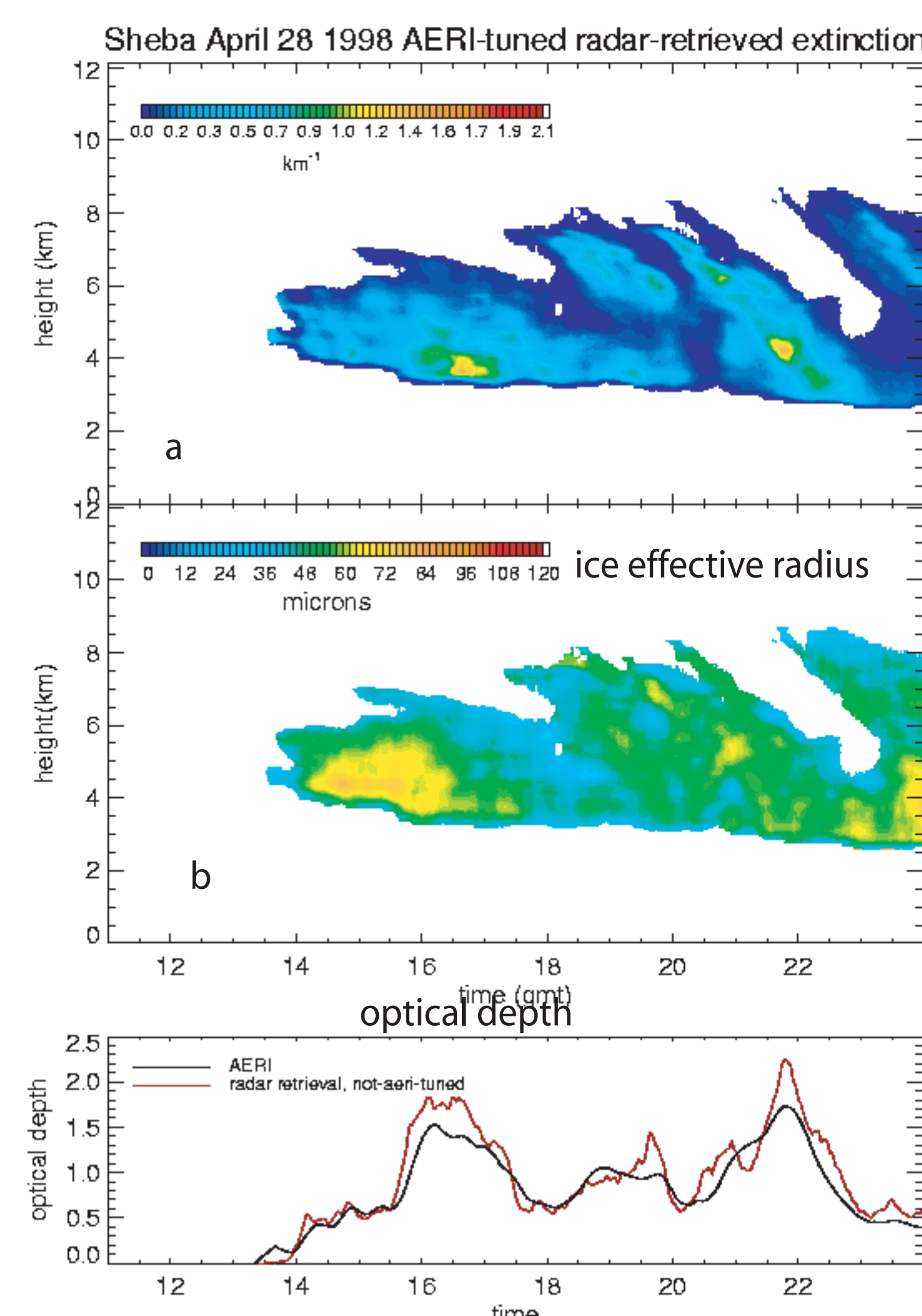
3. The Effective Radius and the Radiative Transfer Simulation

The Streamer code was chosen because of its wide use within the Arctic community, its adaptibility to Arctic-condition inputs, its medium-band spectral resolution, and, in particular, its sophisticated treatment of ice clouds. The longwave ice cloud optical properties are derived through parameterizing Mie calculations following Hu and Stamnes (1993), and the shortwave parameterizations developed for seven different particle habits (Key et al., 2002). 30 different observed particle size distributions form the base of the parameterizations.

Several issues arise with its use: 1) the parameterizations assume a solid ice density, and, 2) only tropical and mid-latitude ice particle size distributions were considered for the optical property parameterizations, and no Arctic clouds

The radar-retrieved ice particle size is NOT linearly related to the effective radius value expected by Streamer

An ice particle bulk density-size approximation appropriate for cloud radar retrievals is

$$\text{bulk ice density} \sim 0.07\ D^{\wedge}(-1.1)$$

where D is the individual particle size. This accounts for the observation that as ice particle sizes increase, they tend to take on more complicated shapes that diminish their bulk density, e.g., rosette forms.

A regression relates the radar-derived D to the solid-ice-density effective radius r expected by Streamer. The solid-ice density effective radius r is shown in Fig. 2b.
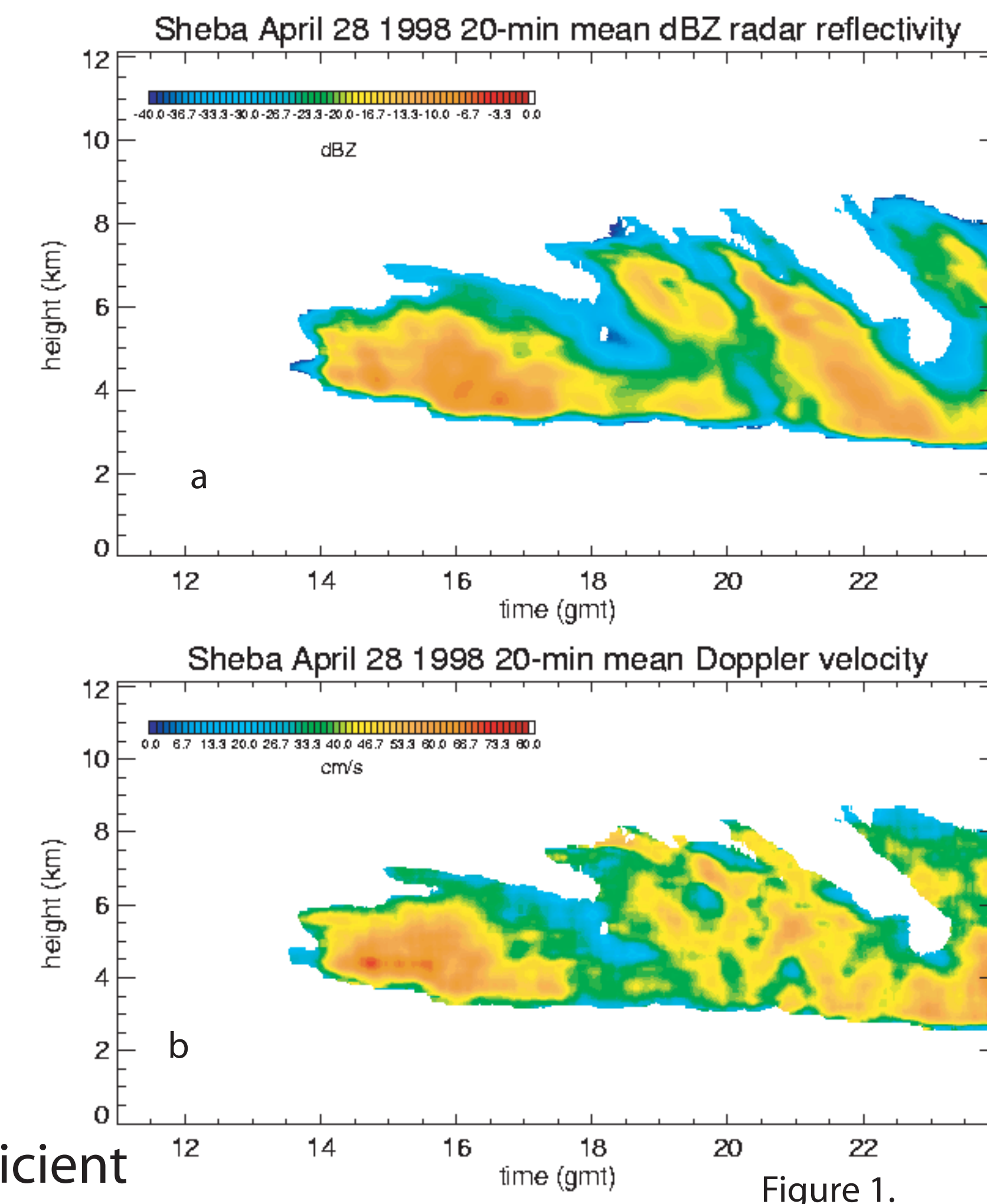
Figure 1.

Figure 2: a) The AERI-tuned radar estimate of the volume estinction coefficient, b) the effective radius, and a line trace of the AERI-derived cloud optical depth against the original radar-only estimate of τ.

References: Key, J. 2001: Streamer User's Guide. *Cooperative Institute for Meteorological Satellite Studies.* 96 pp.
Key, J. , P. Yang, B. Baum, S. Nasiri, 2002: Parameterization of Shortwave Ice Cloud Optical Properties for Various Particle Habits, *J. Geophys. Res., -Atmo.* in press. available online at http://stratus.ssec.wisc.edu/products/icehabits/icehabits.html
Matrosov, S., A. Korolev, A. Heymsfield, 2002: Profiling Cloud Ice Mass and Particle Characteristic Size from Doppler Radar Measurements. *J. Atmo. Oce. Tech.* in press. June-July issue.
Uttal, T. and 27 co-authors, 2002: Surface Heat Budget of the Arctic Ocean, *Bull. Amer. Met. Soc.,*Feb. 255-275.

RESULTS:

4a: How well is the effective radius estimated by the cloud radar ?
- *comparisons to insitu aircraft data*

The insitu data considered here and those upon which the Streamer parameterizations are based are optical probe 2DC aircraft data. These are collected in 25 micron bins with the smallest bin centered on 25 microns; particles less than ~ 20 micron are missed. The particle sizes retrieved using cloud radar and captured by the 2DC probe are thought to be similar for this reason. For the SHEBA case, in situ and remote estimates of particle size and ice water content correspond well (Matrosov et al., 2002).

Fig. 3 shows the SHEBA insitu size distribution data collected during a spiral descent occurring between 23:55 to 00:15 UTC. Most particles were irregular aggregates with approximately equal dimensions along both optical axes. 135 measurements were made; in Fig. 3, three averages of 45 measurements each were constructed according to their height within the cloud. The range of the Streamer size distributions is also shown. In comparison to the tropical and mid-latitude size distributions, the Arctic size distribution shows a high proportion of small particles and a small proportion of large particles.

Fig. 2. Three of the 30 Fu size distributions obtained from aircraft measurements. The other size distributions fall within the size and number concentration ranges of these three.
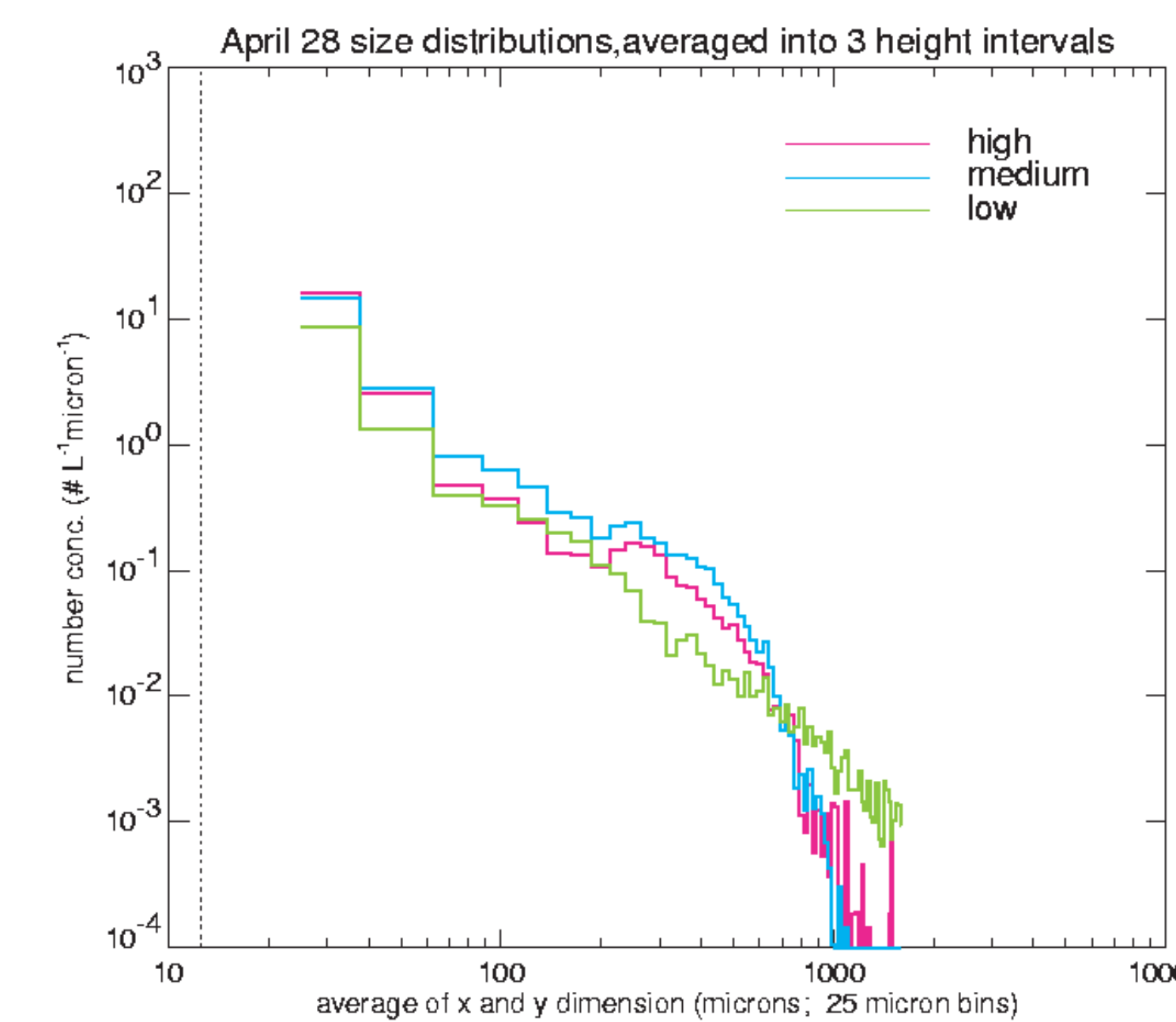
from Key et al., 2002

Fig. 3:

To account for the missed small particles within the Streamer parameterizations, the optical probe data were extrapolated to smaller sizes using a power law form (see figure from Key et al. (2002) above). The SHEBA aircraft particle size data were similarly treated to estimate a population of particles of size 12.5 microns. **The addition of a population of small particles led to a calculated 5-6% increase in β and a 6% decrease in the effective radius r.** Additionally, ice water content increased 1 %, and the radar reflectivity changed negligibly.
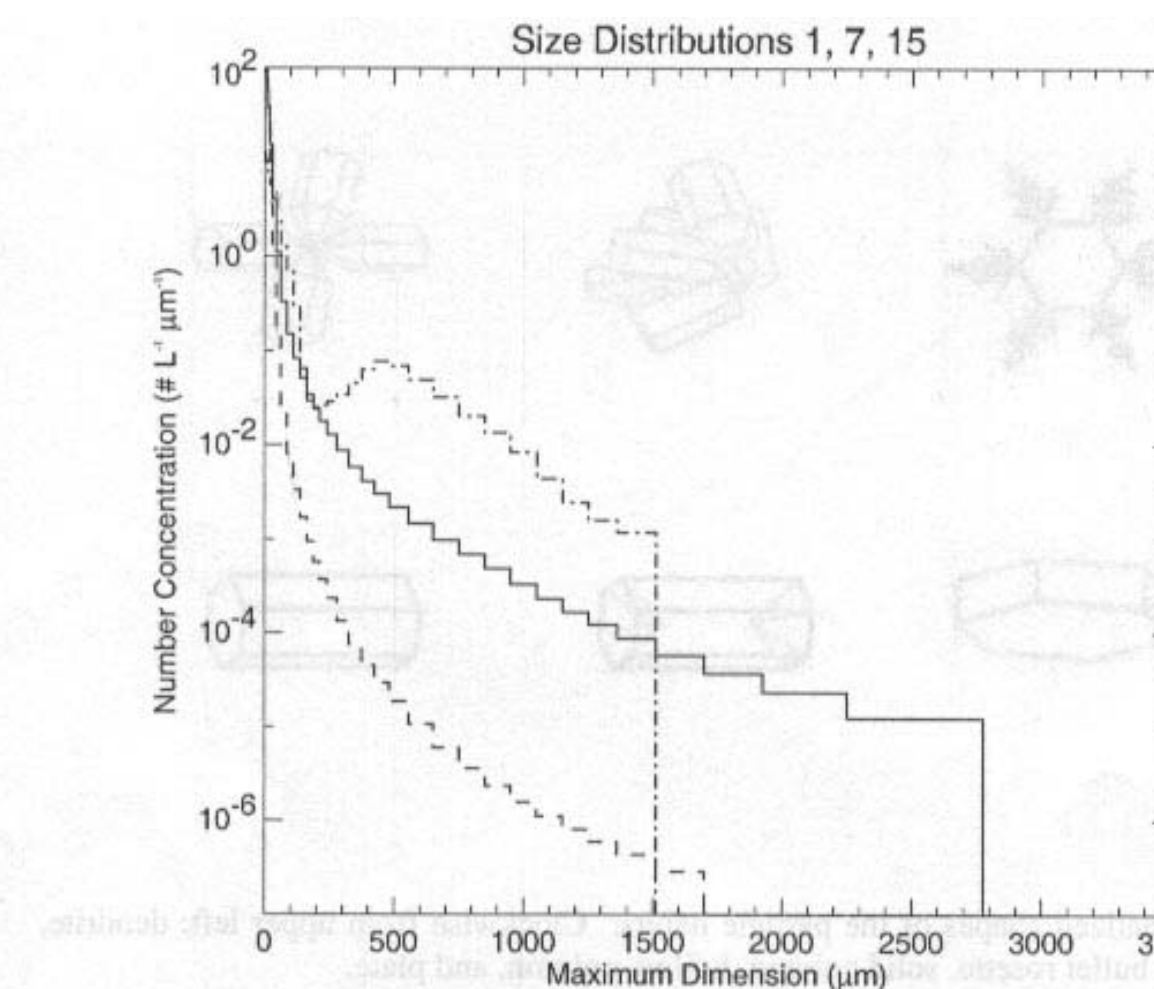
4b: How does the addition of small particles change the net radiative heating field ?

Fig.4 shows the best estimate of the net radiative heating rate field (all-sky - clear-sky) for this case. The extinction field is as shown in Fig. 2a, the effective radius is 95% of that shown in Fig 2b (to incorporate the result of 4a), a spherical particle habit is assumed for particle median sizes less than 36 micron and an aggregate shape is assumed for the larger particles.

Fig. 5 shows the difference in radiative heating between a cloud as described by Fig. 2 and one in which the effective radius is equal to 90% of that shown in Fig 2b. The cloud **with smaller particles but the same optical depth cools slightly more: roughly 5% at the most.** This may be an underestimate, as no particles smaller than 12.5 microns are considered, and the 2DC probe is known to undercount its smallest bins.
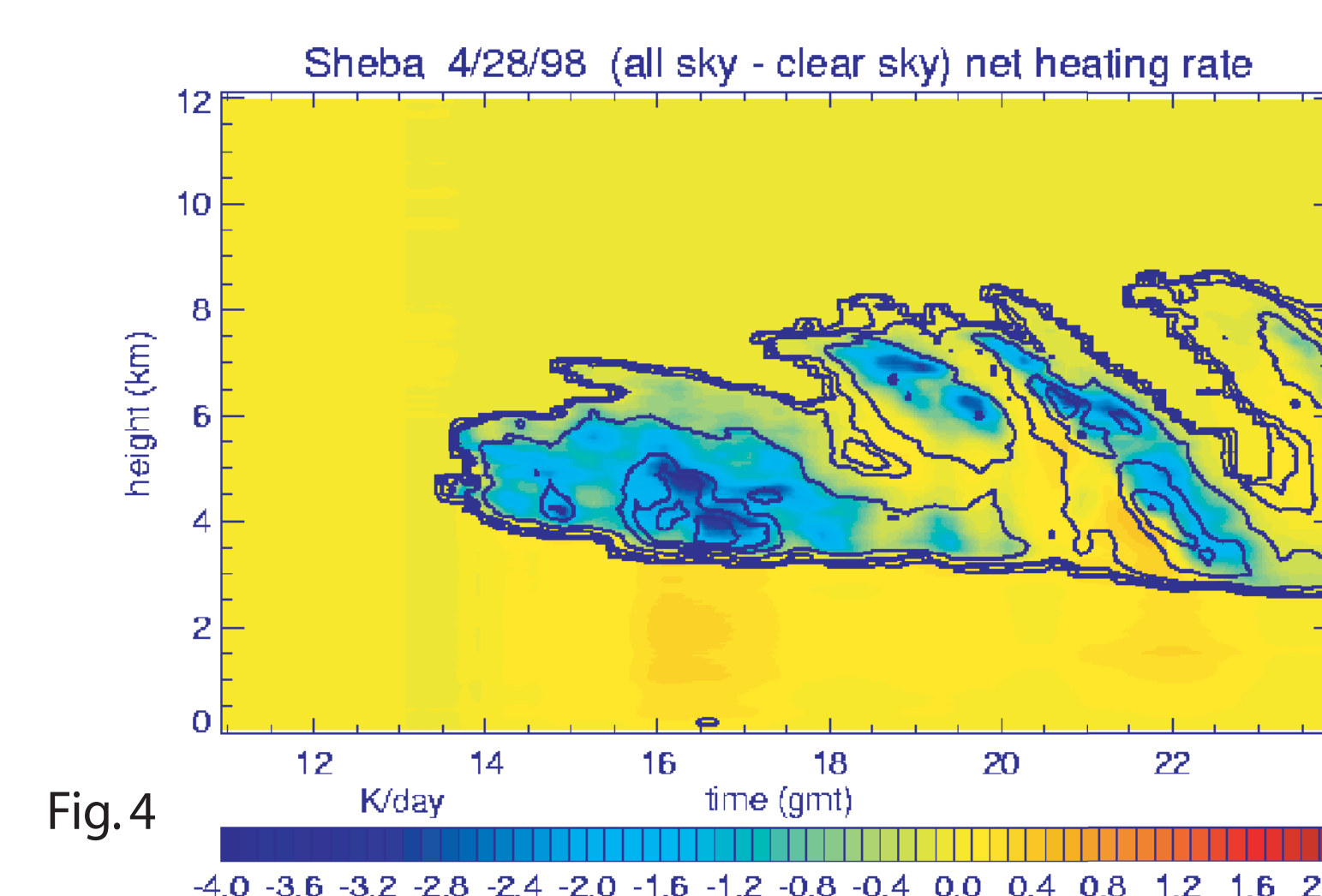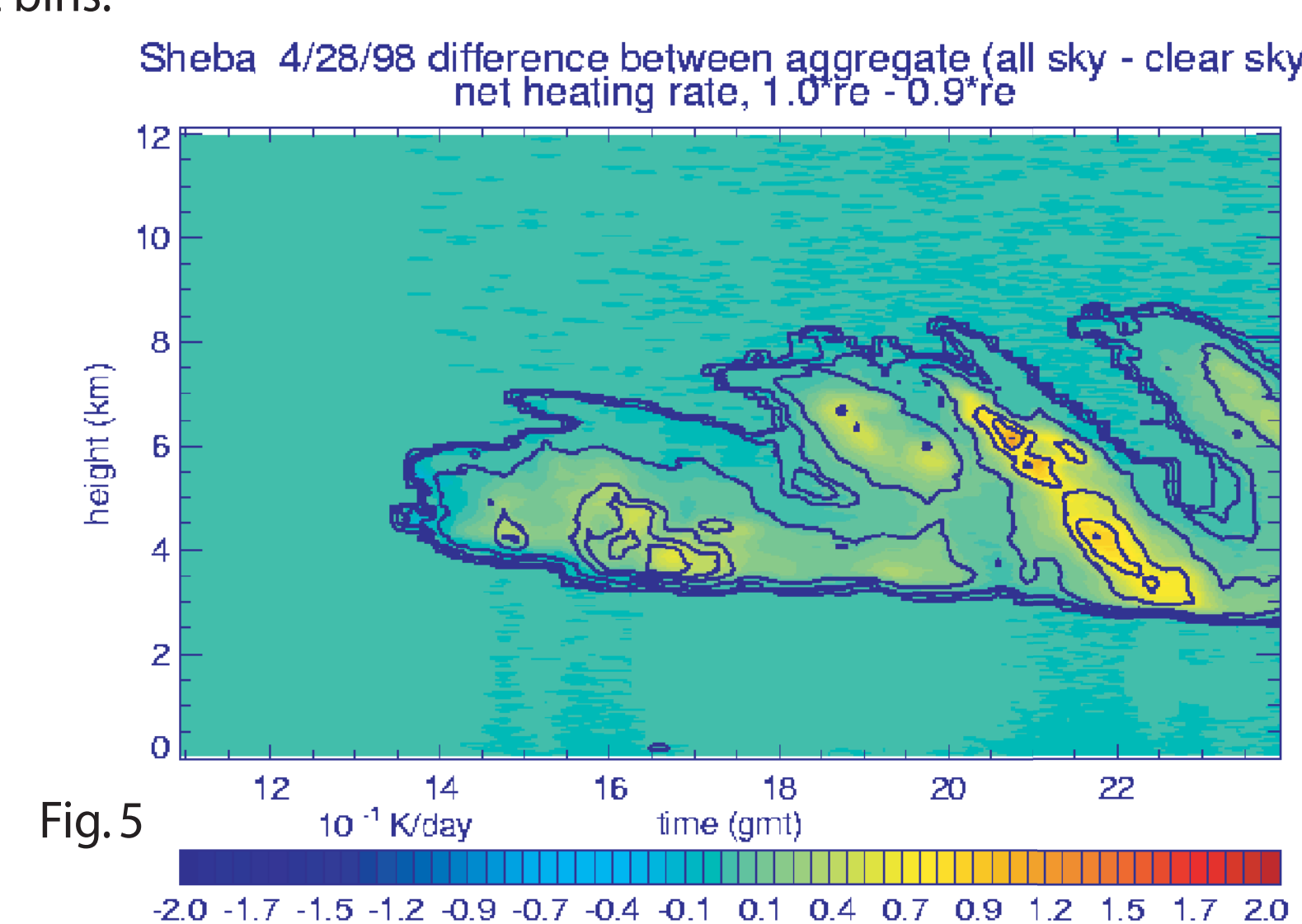
Fig. 4

Fig. 5

5. Conclusions and Summary

An evaluation was done of realistic errors that can be produced in Arctic radiative heating rate fields if, when using cloud radar-derived microphysical properties as inputs, 1) particles too small to be detected by radar are included, and 2) particle habit is inaccurately specified. In situ aircraft data were used to estimate the number of missed small particles and to establish a reference particle habit. We find:

1) The neglect of small particles can cause underestimates of up to 5% in the local net radiative heating rate
2) The inaccurate specification of ice particle habit can generate differences of up to 15% in local net radiative heating rates from the reference case. These differences can be of either sign.

Based on one case study alone:
1) the initial neglect of small particles by the cloud radar can be easily accounted for with a correction to the effective radius input into Streamer
2) Significant error in the cloud radiative heating rate calculation can result from a lack of a priori knowledge of ice particle habit

4c: What is the impact of particle habit on the net radiative heating field ?

The SHEBA aircraft data determines the predominant particle form are irregular aggregates. Fig. 6 shows the surface shortwave cloud forcing for seven particle habits (all particles smaller than 36 micron mean size are still assumed to be spheres), and for aggregates assumed to have 90% the effective radius of the original retrieval. Solar noon occurs around 22 UTC.
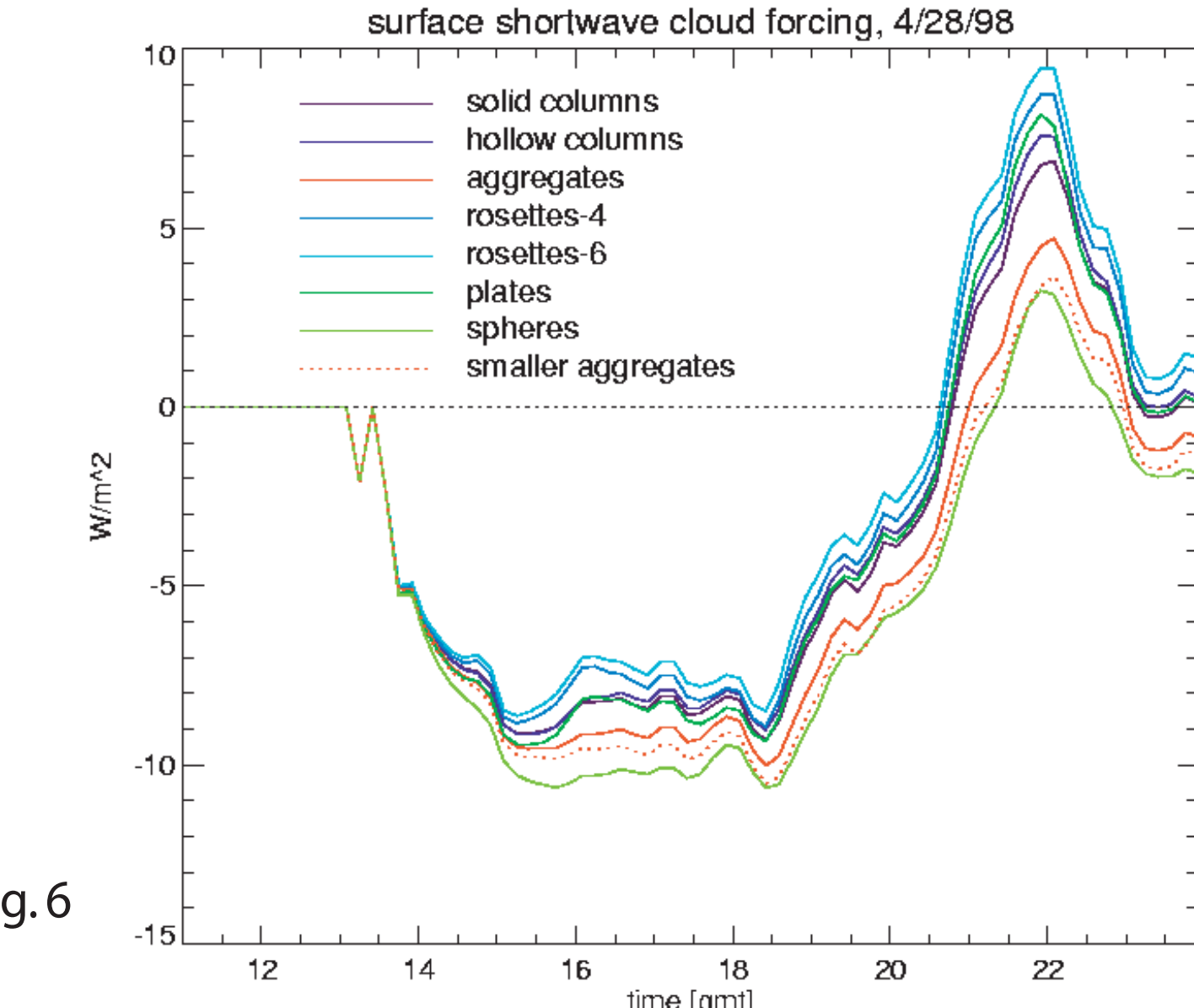
Fig. 6

Fig. 7 shows the difference in radiative heating between a cloud composed of aggregates, and a) of bullet rosettes with 6 branches, and b) of spheres. These habits show the largest differences from aggregates in their net radiative heating fields. **For this case, a cloud with inaccurately-determined particle shapes can produce differences in local heating of up to 15% of either positibve or negative sign**
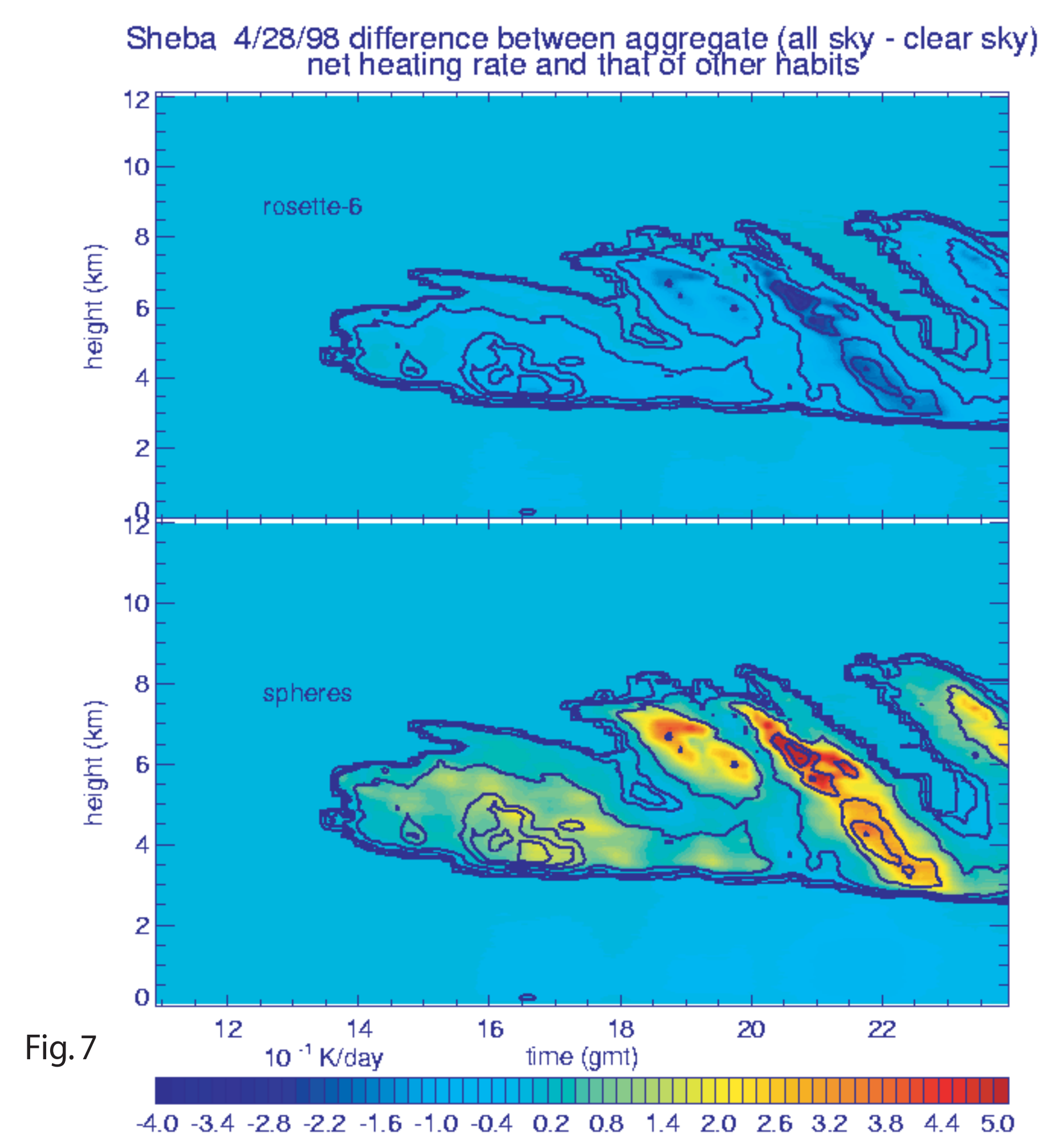
Fig. 7